Lidar Measurements of Atmospheric CO_2 from Regional to Global Scales

Bing Lin[1], F. Wallace Harrison[1], Amin Nehrir[1], Edward Browell[2], Jeremy Dobler[3], Joel Campbell[1], Byron Meadows[1], Michael Obland[1], Syed Ismail[1], Susan Kooi[4], Tai-Fang Fan[4], and LaRC ASCENDS team

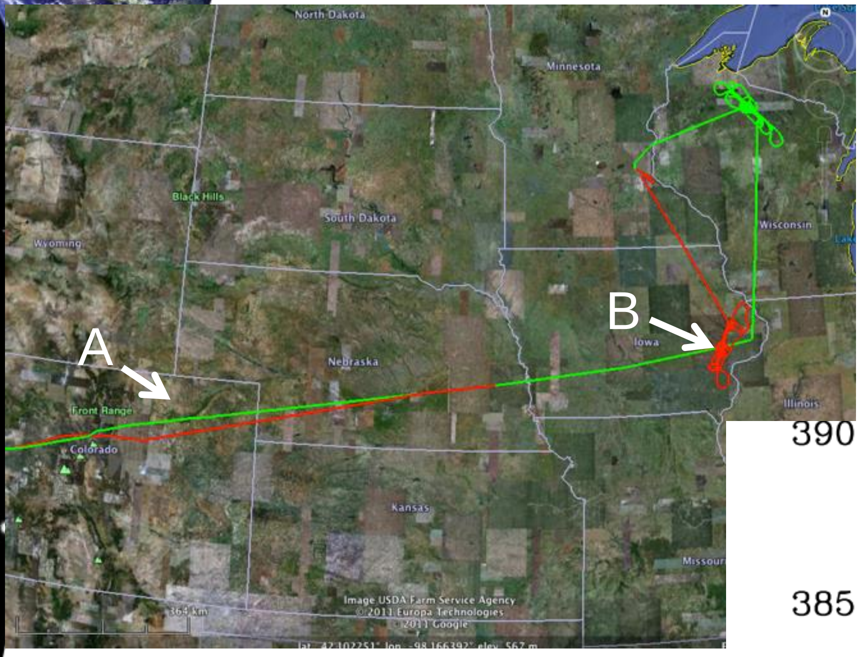
[1]NASA Langley Research Center, Hampton, VA, USA
[2]NASA Langley/STARSS II Affiliate, Hampton, VA, USA
[3]Exelis Inc., Ft. Wayne, IN, USA
[4]Science System and Application, Inc, Hampton, VA, USA

Japan Geoscience Union Meeting 2015
27 May 2015, Chiba, Japan

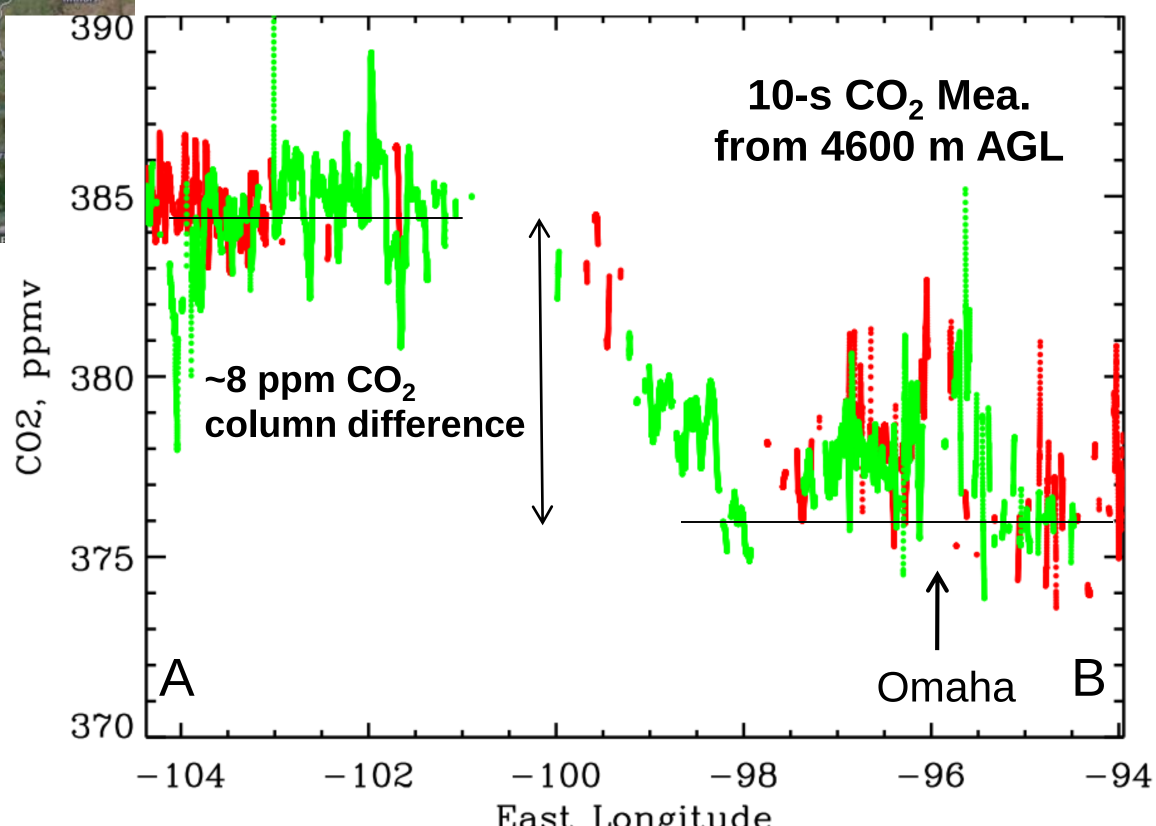
Outline

- **Introduction**
  - **Carbon sciences and challenges**
  - **Instrumentation**
- **CO_2 Measurements**
  - **Ranging measurements**
  - **Various surface conditions**
  - **Accuracy and precision**
  - **Clouds: thin or thick**
  - **Space application**
- **Summary**

Grand Challenge: small gradient

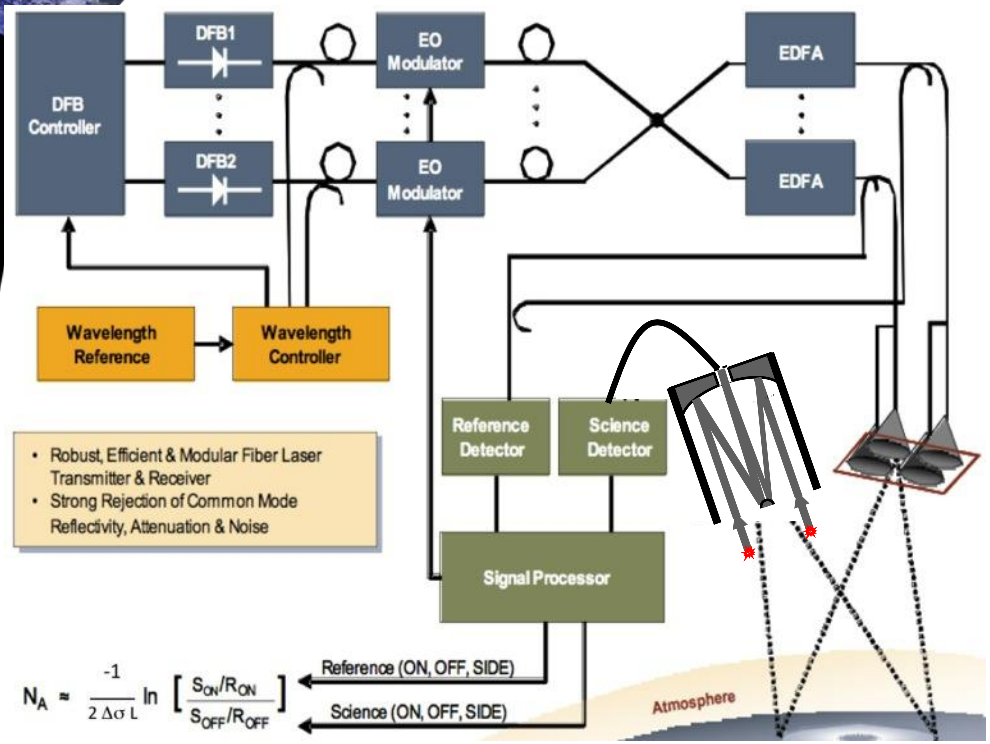


Midwest Flights
Flight 6, 10 August 2011
Flight 7, 11 August 2011



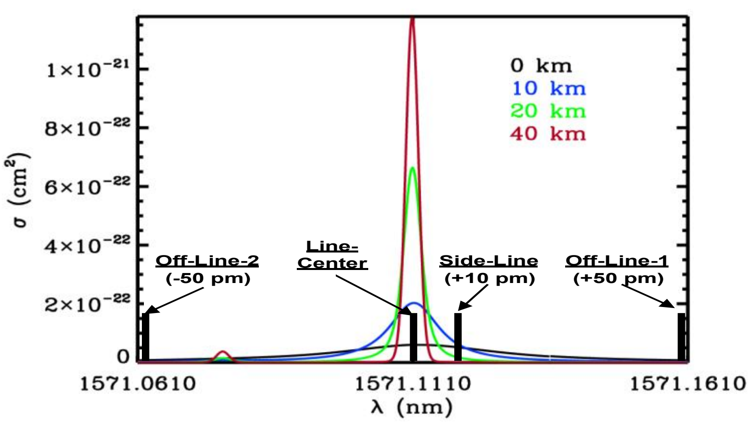
- **CO_2 uptake observed over corn fields in E. Nebraska & Iowa.**
- **Higher CO_2 observed over Colorado & W. Nebraska.**
- **Enhanced CO_2 found in vicinity of Omaha.**

Multifunctional Fiber Laser Lidar (MFLL) 1.57-μm CO_2 Measurement Architecture

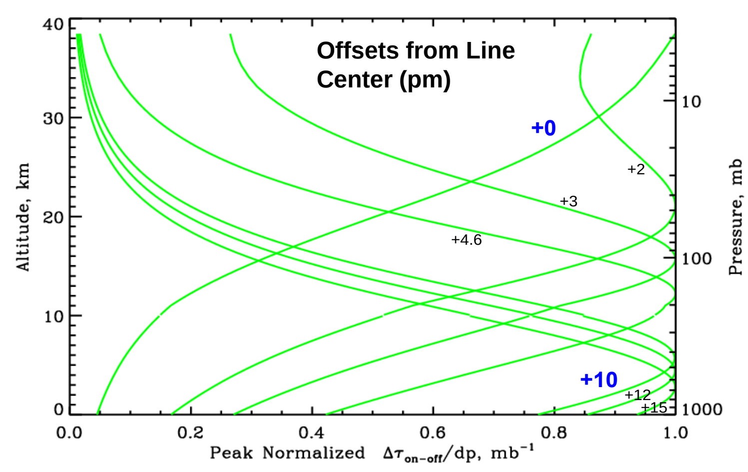


– Simultaneously transmits λ_{on} and λ_{off} reducing noise from the atmosphere and eliminating surface reflectance variations.

– Approach is independent of the system wavelength and allows simultaneous CO_2 & O_2 (1.26 μm) measurements for deriving XCO_2 measurement.



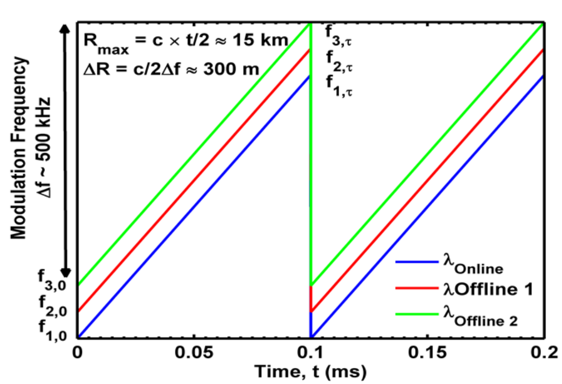
Weighting Functions

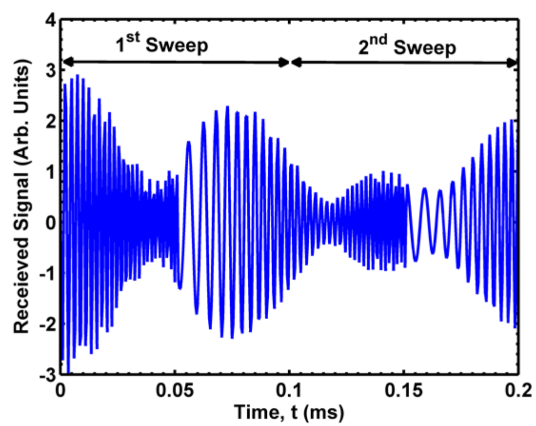


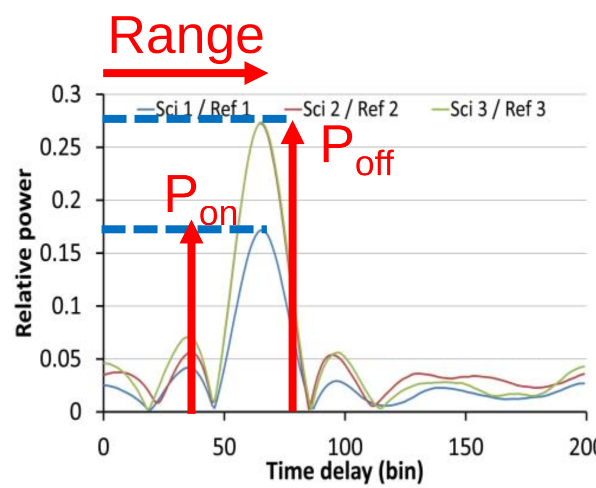
Multifunctional Fiber Laser Lidar (MFLL) 1.57-µm CO_2 Measurement Technique

Progression of Transmitted and Received Intensity-Modulated Waveforms

Simultaneously transmitted Intensity modulated range encoded waveforms	Simultaneously received Online and Offline IPDA returns	Measurement: Output of correlation between transmitted and received waveforms







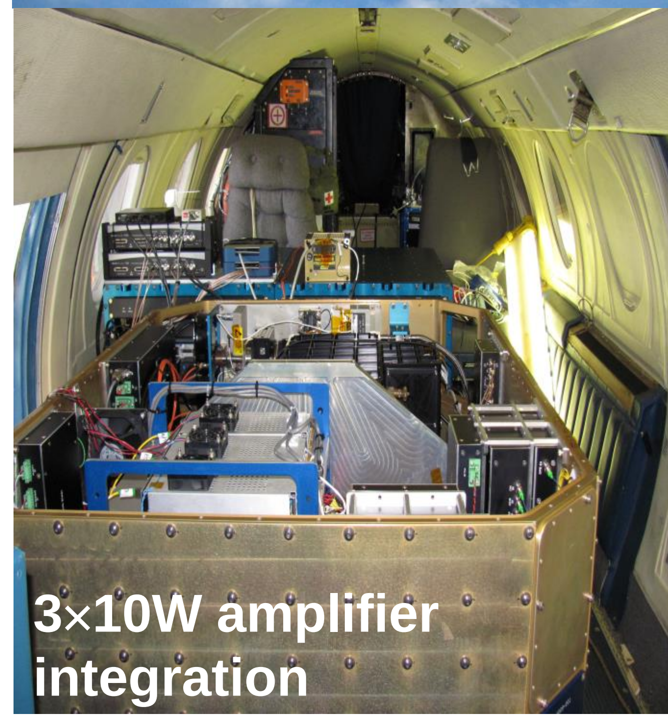
Range encoded approach for detection and ranging is analogous to mature FM-CW Radar and GPS measurement techniques

$$DAOD = \frac{1}{2} ln\left(\frac{P_{off} * E_{on}}{P_{on} * E_{off}}\right)$$

Instrument Development
(joint effort of LaRC and Exelis)

ASCENDS CarbonHawk Experiment Simulator (ACES developed at LaRC with support from Exelis)

Multifunctional Fiber Laser Lidar (MFLL) (developed by Exelis in 2004 Exelis and Langley since 2005)



3×10W amplifier integration

Instrument-aircraft integration

advancing key technologies for spaceborne measurements of CO_2 column mixing ratio

Development & Demonstration

ASCENDS

21-25 May 2005, Ponca City, OK (DOE ARM)
5 Lear Flts: Land, Day & Night (D&N)

20-26 June 2006, Alpena, MI
6 Lear Flts: Land & Water (L&W), D&N

20-24 October 2006, Portsmouth, NH
4 Lear Flts: L&W, D&N

20-24 May 2007, Newport News, VA
8 Lear Flts: L&W, D&N

17-22 October 2007, Newport News, VA
9 Lear Flts: L&W, D&N, Clear & Cloudy

22 Sept. – 30 Oct. 2008, Newport News, VA
10 UC-12 Flts: L&W, D&N, Rural & Urban

10-16 July 2009, Newport News, VA
5 UC-12 Flts: L&W

31 July – 7 Aug. 2009, Ponca City, OK
5 UC-12 Flts: L&W, D&N

10-20 May 2010, Hampton, VA
6 UC-12 Flts: L&W, D&N

5-11 May 2011, Hampton, VA
5 UC-12 Flts: L&W, D&N, Clear and Cloudy

6-18 July 2010, Palmdale CA
6 DC-8 Flts: L&W, D

28 July – 11 Aug. 2011, Palmdale CA
8 DC-8 Flts: L&W, D

February 19 – March 9, 2013, Palmdale CA
7 DC-8 Flts: L&W, D&N

August 13 – September 3, 2014, Palmdale CA
5 DC-8 Flts: L&W, D

MFLL on Lear-25

MFLL on UC-12

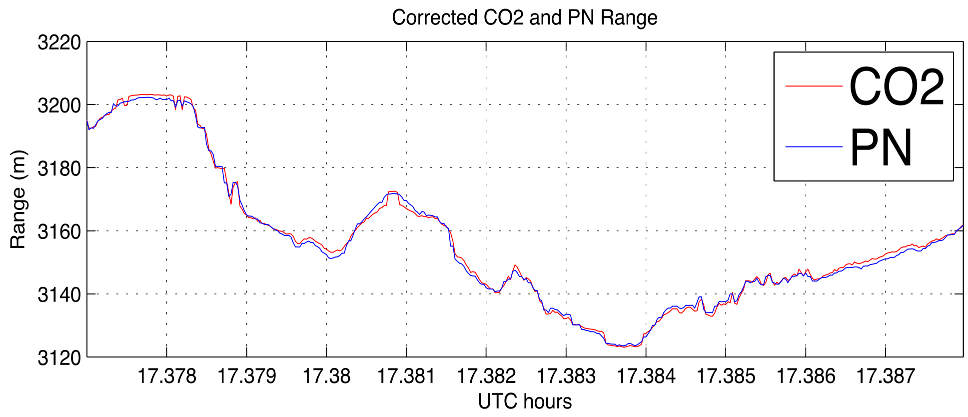
MFLL on DC-8

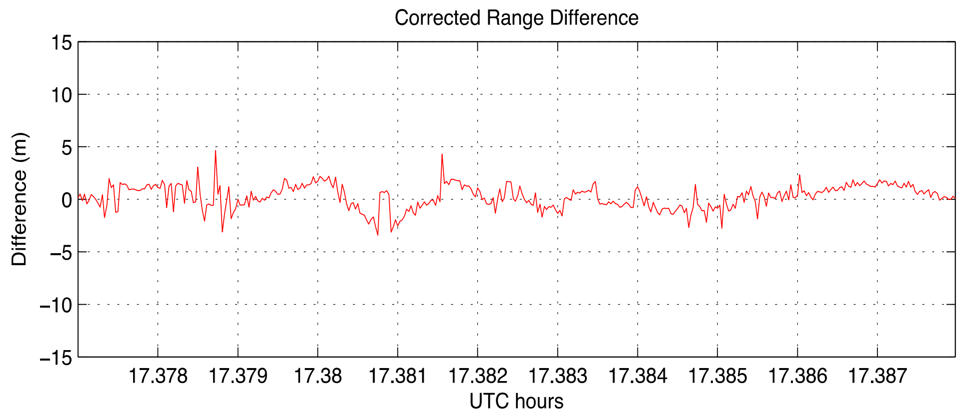
ranging capability enabled

various lab, ground range, and flight tests

total 14 MFLL flight campaigns since 2005, plus 1 ACES in Hampton, 2014

Comparison of Range Determination from PN Altimeter and Off-line CO_2 Signal



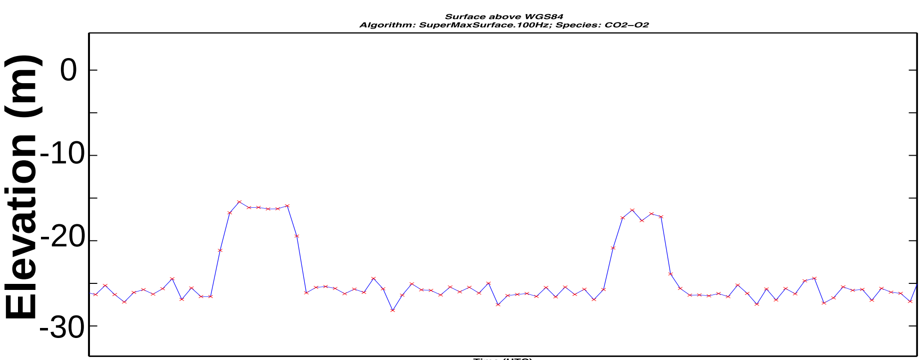


RMS errors < 3 m

Range estimates obtained from the off-line CO_2 return and time coincident returns from the onboard PN altimeter over the region of Four Corners, NM from the DC-8 flight on 7 August 2011.

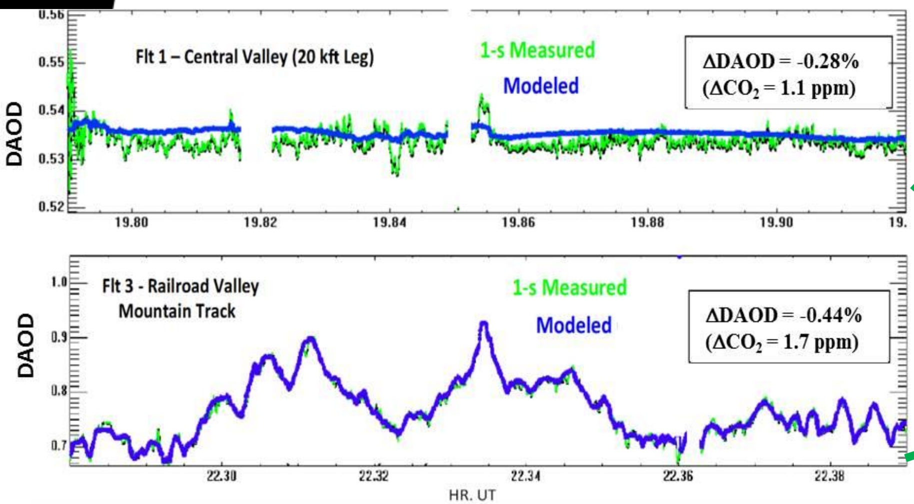
Ranging over Hampton Roads
(ACES in June 2014)

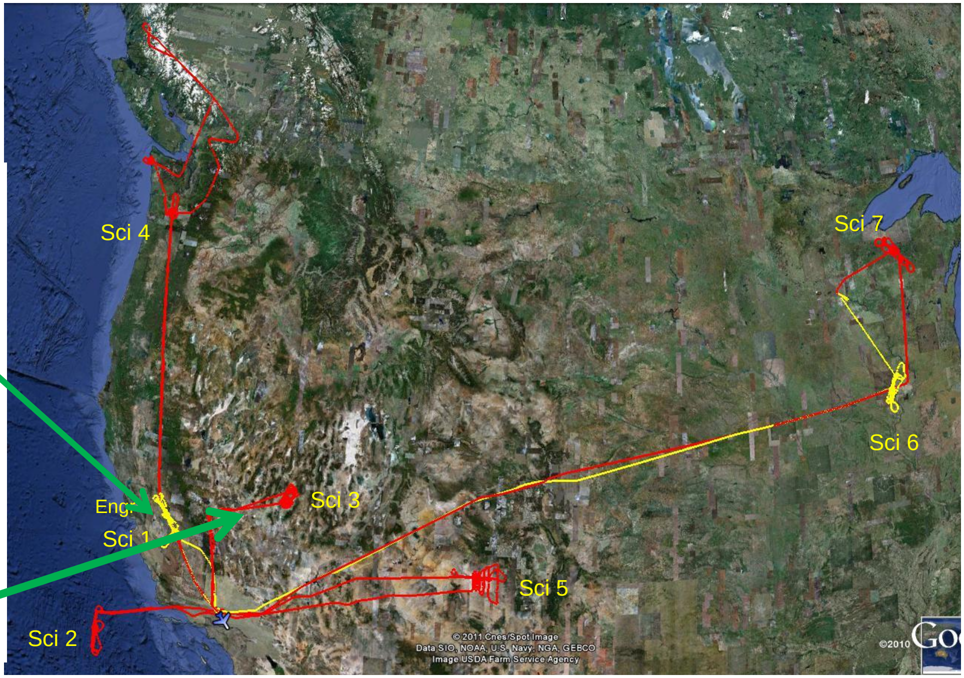
Chesapeake Bay Bridge



2011 ASCENDS DC-8 Flight Campaign
28 July – 11 August

Differential Absorption Optical Depth (DAOD) Comparisons





SNR Comparisons

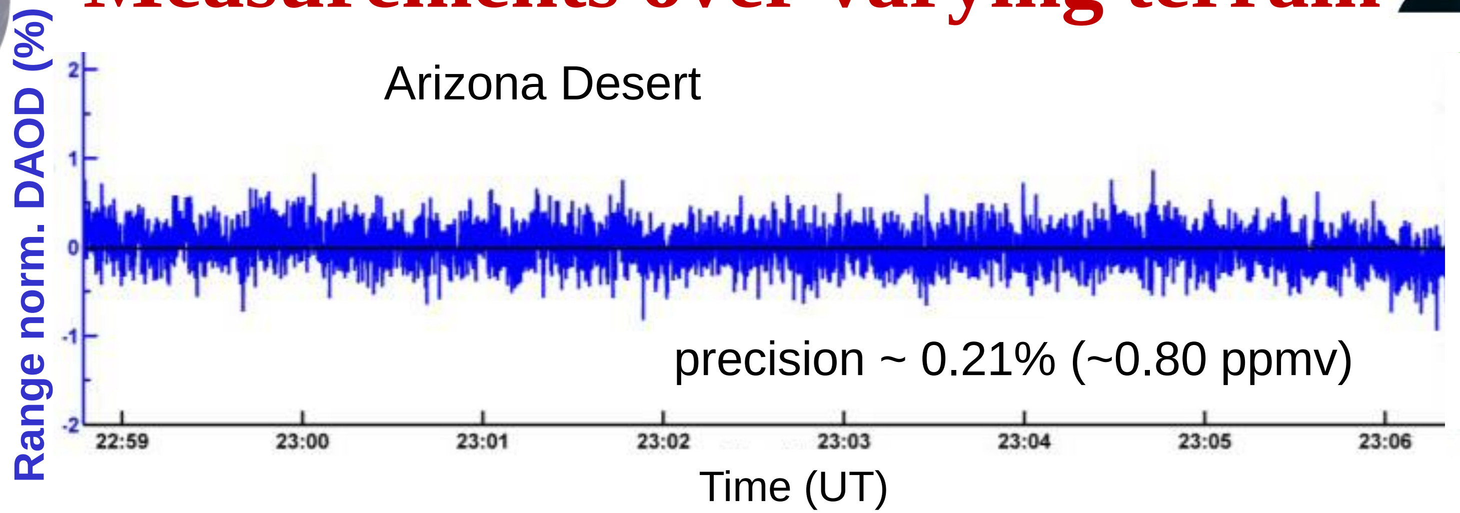
Flight #	Start Hour	End Hour	Delta Time, sec	Nadir Range, m	Optical Depth	CO2, ppmv	1-s SNR	1-s ! , ppmv	10-s SNR	10-s ! , ppmv
1	20.07	20.08	198.0	6406	0.708	389.7	433	0.90	1264	0.31
3	20.03	20.06	211.0	6593	0.755	394.5	517	0.76	1510	0.26
4	15.63	15.70	396.0	6360	0.704	387.1	460	0.84	1325	0.29
5	20.00	20.02	180.0	8063	0.924	391.8	418	0.94	1274	0.31
7	17.21	17.23	79.2	5805	0.632	379.2	396	0.96	1237	0.31

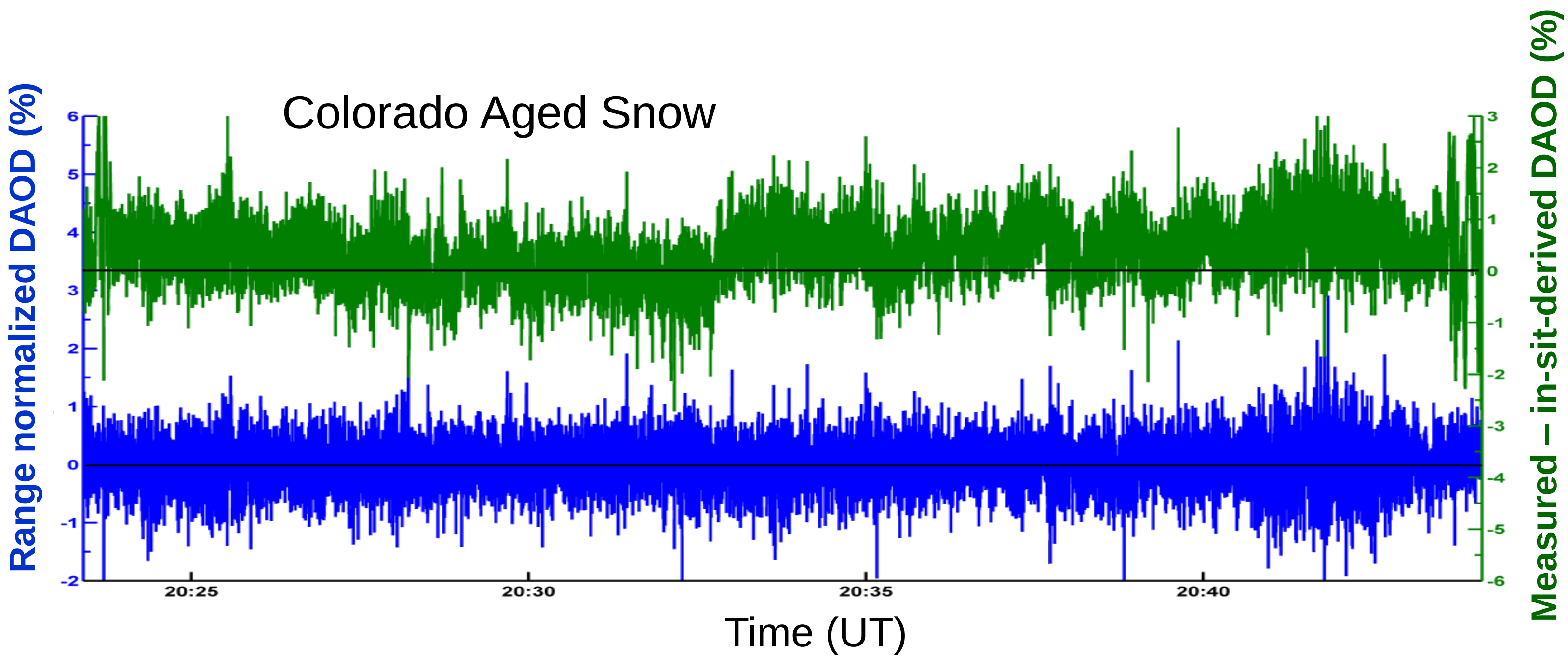
Avg:	6645	0.745	388.5	445	0.88	1322	0.29

Modeled DAOD: in-situ XCO2 measurements + radiative transfer model to calculate CO2 absorption optical depth

2013 ASCENDS Campaign: Measurements over varying terrain

1-s average

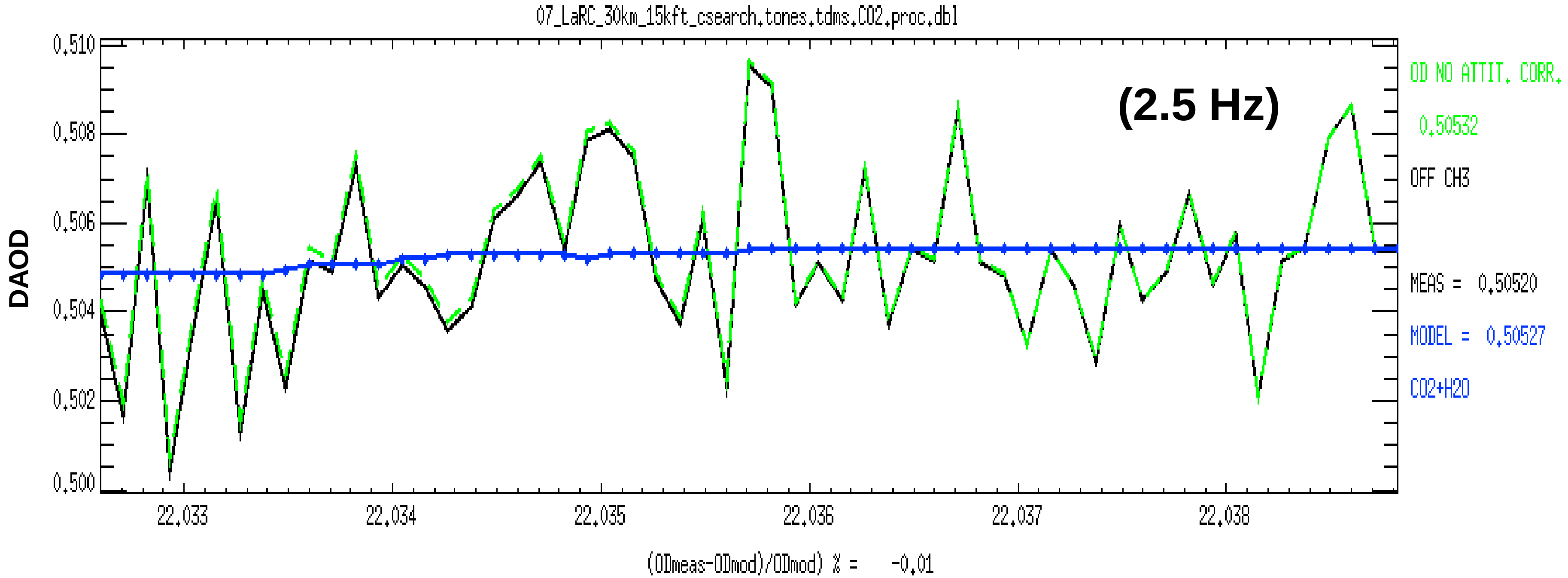




difference ~ 0.26% (~0.99 ppmv); Precision ~ 0.42% (~1.6 ppmv)

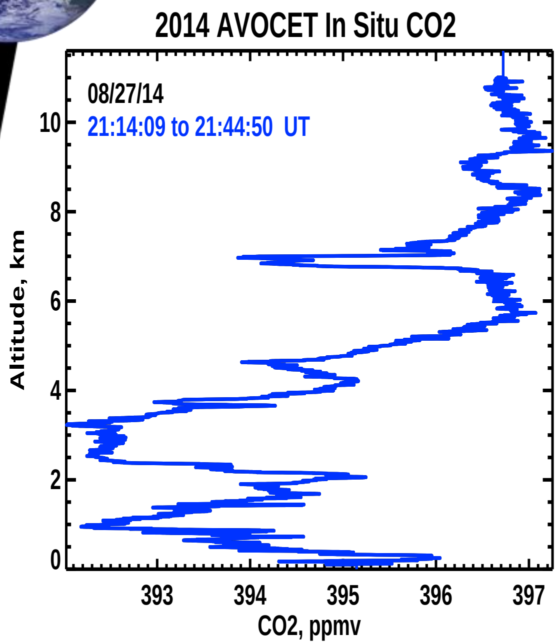
Winter 2013 Flight Campaign

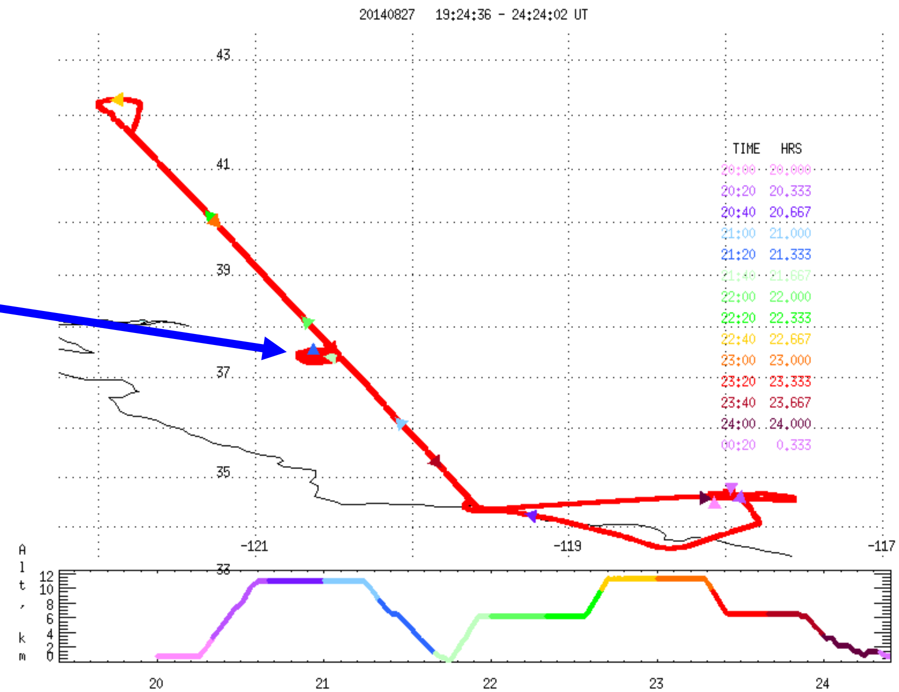
Feb. 22, 2013 Flight: Blythe, CA
Comparison of CO_2 columns from MFLL measurements and model calculations (derived from in situ)

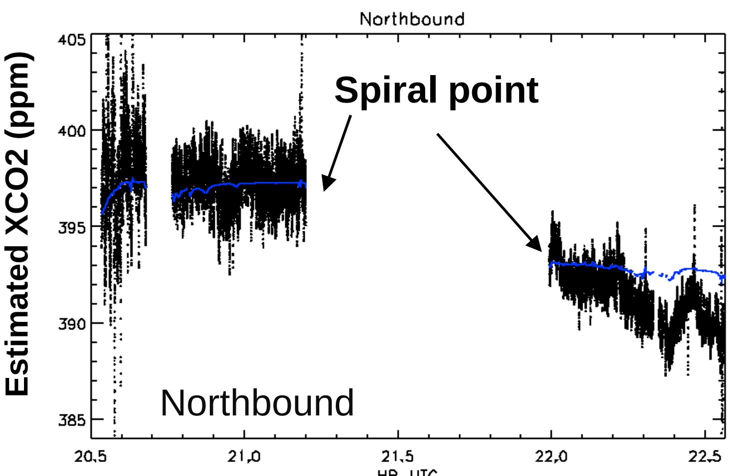


$(DAOD_{mea} - DAOD_{mod})/DAOD_{mod}$ = - 0.01% (or within 0.04 ppm)

OCO-2 Flight: 20140827







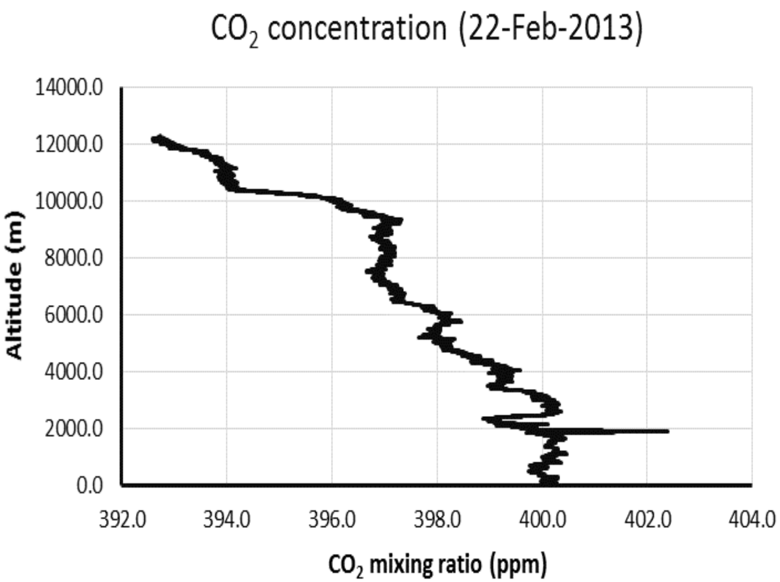
Black curves: lidar measured XCO2
Blue curves: in-situ derived XCO2

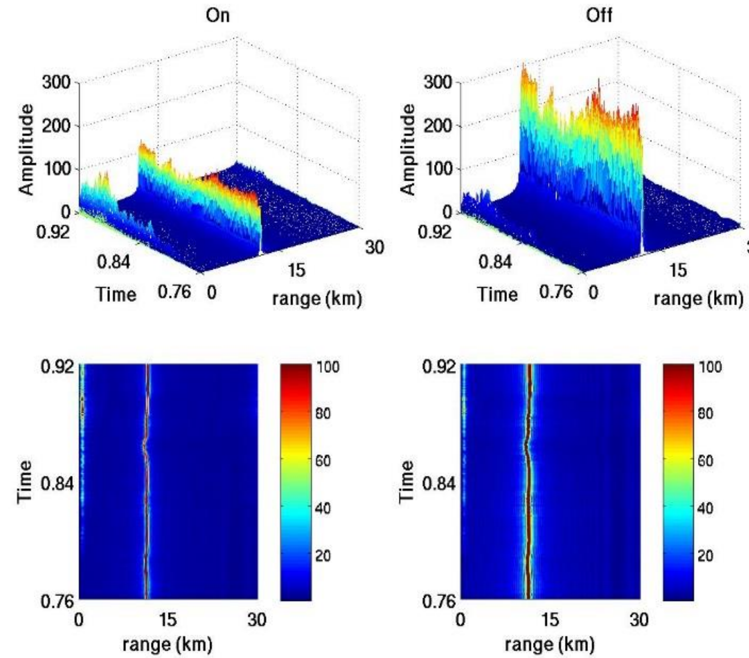
Significant XCO_2 variability

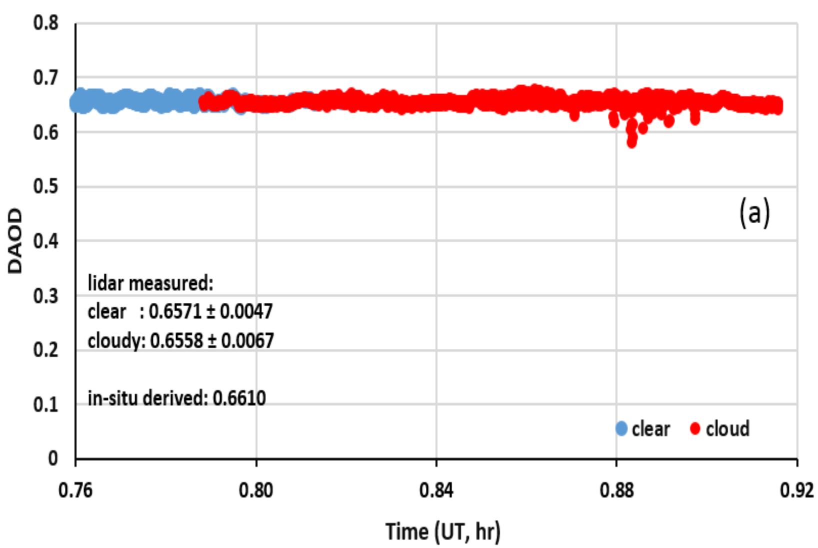
High spatiotemporal coverage of in-situ measurement needed

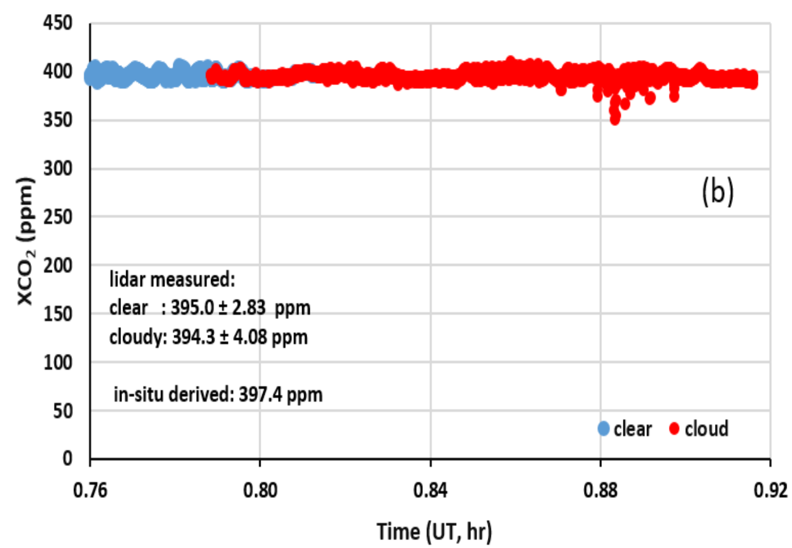
differences (ppm):
0.08, 0.18, 0.94, 0.19

CO_2 Column Measurements Through Thin Cirrus (22 Feb 2013)





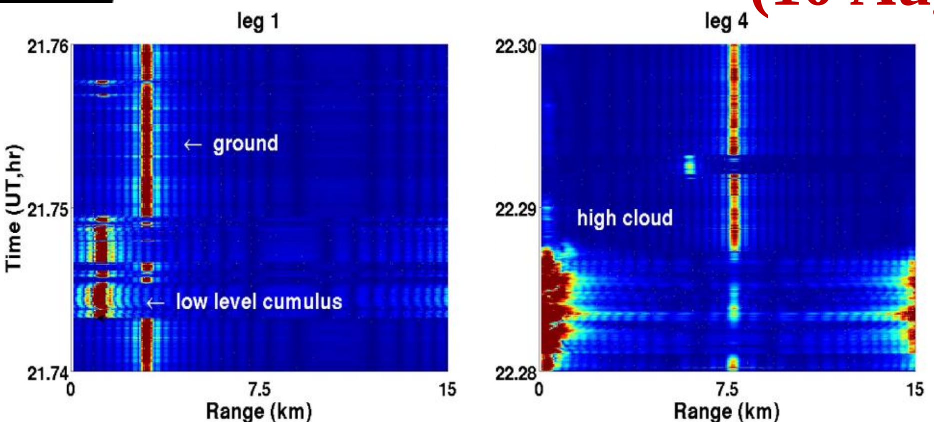


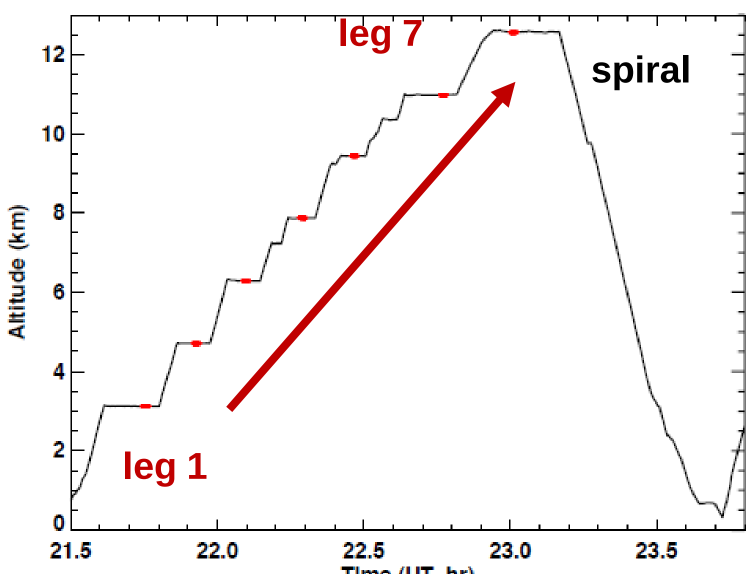


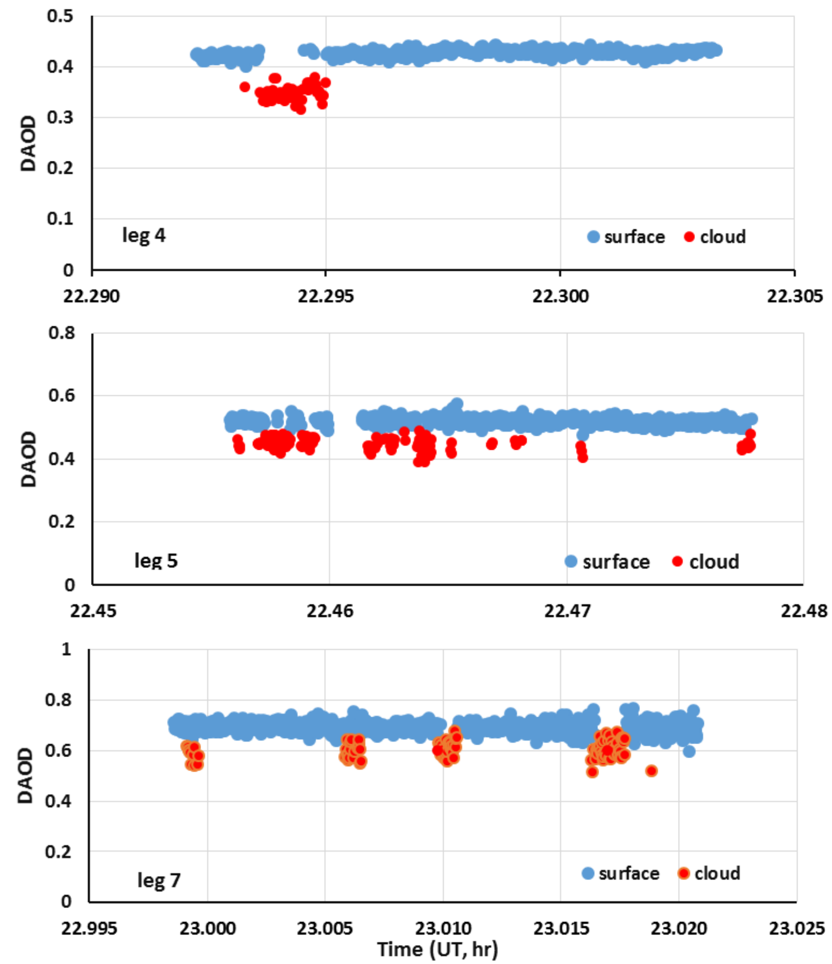
ata

CO_2 Column Measurements over Thick Low Level Clouds

(10 Aug 2011)







legs: 4, 5, 7

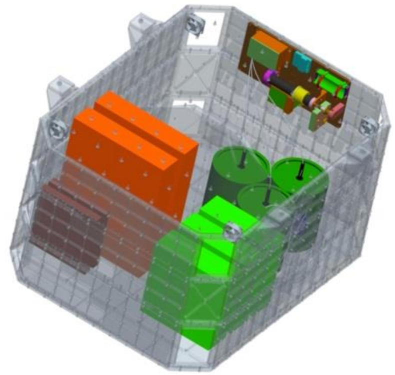
Column CO_2 Measurements to Surface and Thick Cloud Tops

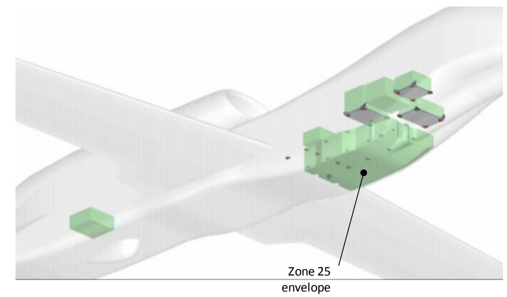
	Leg 4	Leg 5	Leg 7
lidar $DAOD_{surface}$	0.4271 ± 0.0056	0.5196 ± 0.0093	0.6902 ± 0.0155
lidar $DAOD_{cloud}$	0.3480 ± 0.0143	0.4368 ± 0.0243	0.6007 ± 0.0339
In-situ $DAOD_{surface}$	0.4243	0.5160	0.6939
In-situ $DAOD_{cloud}$	0.3417	0.4334	0.6075
lidar $XCO2_{surface}$	383.2 ± 5.02	384.3 ± 6.88	381.6 ± 8.57
lidar $XCO2_{cloud}$	391.5 ± 16.09	387.7 ± 21.31	382.0 ± 21.56
In-situ $XCO2_{surface}$	380.8	381.7	383.8
In-situ $XCO2_{cloud}$	384. 6	384.9	386.4

10 Hz data

ASCENDS Mission Development

Current





Today: MFLL and ACES instruments in DC-8 racks

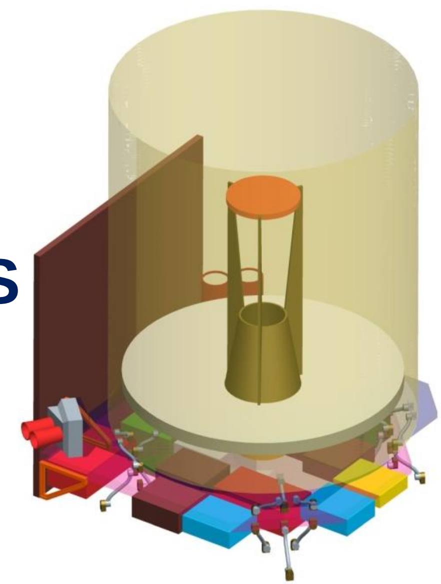
Global Hawk

Size = 100” x 43” x 24” Mass = 787.2 lb.	Size = 44” x 34” x 24” Mass = 317.1 lb

Future

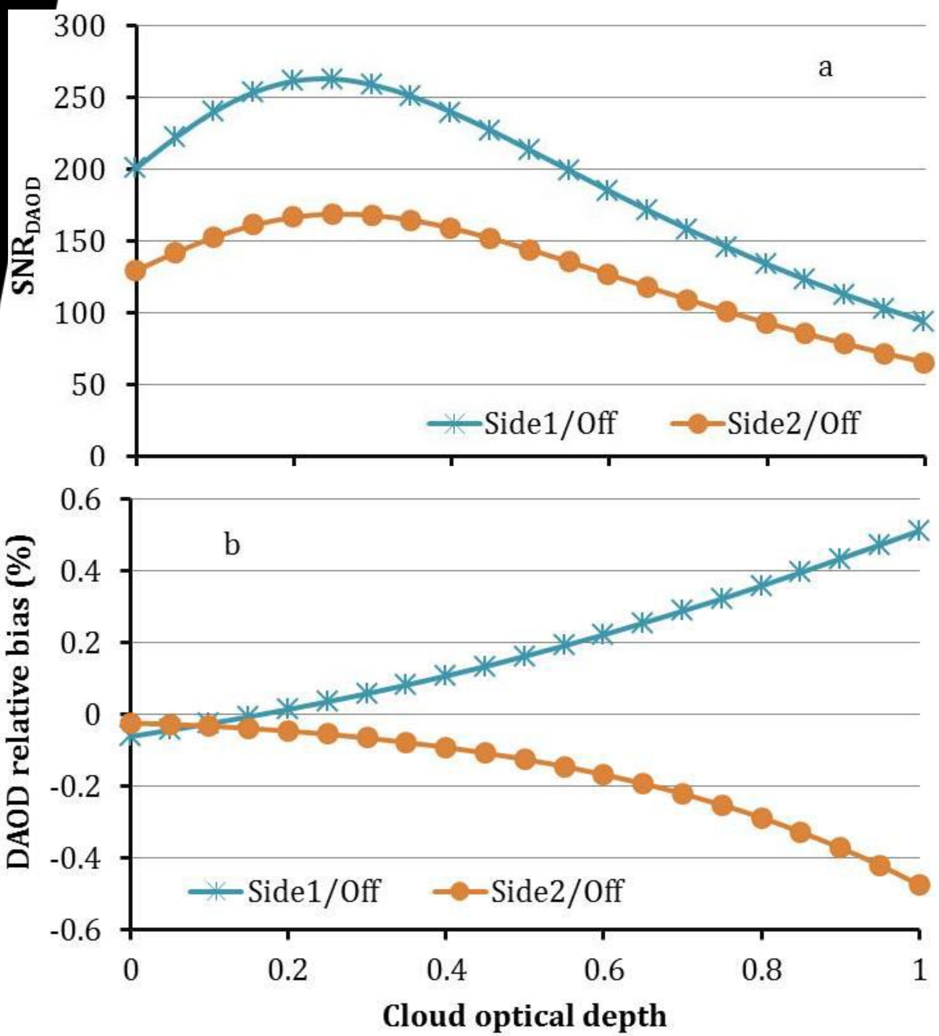
TBD: ISS Tech Demo?

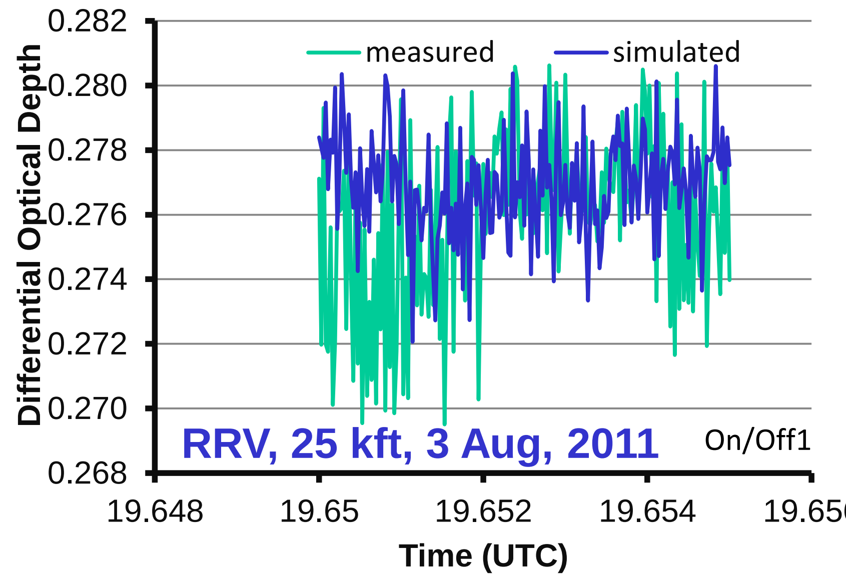
TBD: ASCENDS mission



Space CO_2 Lidar Modeling and Measurement

same instrument architecture: increased power and telescope





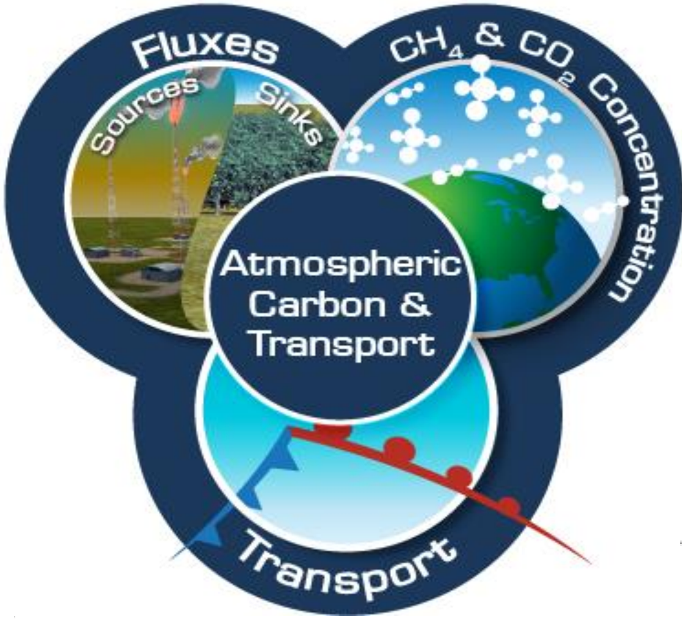
cloud height: 9 km
0.1-s integration time
high SNR & small bias (< 0.25%)
DAOD < ~0.7

dawn/dusk orbit, 42W power

Summary

- Global/regional atmospheric CO_2 observations require high accuracy and precision measurements owing to very small variations in atmospheric CO_2 mixing ratio.
- Laser absorption lidar at 1.57μm with ranging-encoded IM provides advanced capability in cloud/aerosol discriminations. Ranging uncertainties are shown to be below sub-meter level.
- IM-CW lidar has demonstrated the capabilities of precise CO_2 measurements through many airborne flight campaigns under variety of environment conditions, including CO_2 column measurements through thin cirrus clouds and to thick clouds. Over land, clear-sky CO_2 measurement precision within 1-s integration is within 1 ppm while mean bias is much smaller.
- Analysis shows that current IM-CW lidar approach will meet space CO_2 observation requirements and provide precise CO_2 measurements for carbon transport, sink and source studies.

Atmospheric Carbon & Transport (ACT) – America



The ACT-America suborbital mission addresses the three primary sources of uncertainty in atmospheric inversions: atmospheric transport, sources and sinks of carbon, and atmospheric concentration measurements.

Penn State
NASA
LaRC, WFF, GSFC, JPL
Exelis, Colorado State
NOAA ESRL/U Colorado
DOE Oak Ridge, U Oklahoma
Carnegie Inst. Stanford